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A STUDY OF INTERMODULATION INTERFERENCE IN A MULTITRANSMITTER-MULTIRECEIVER ENVIRONMENT

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ABSTRACT

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This report explains how one estimates the level of transmitter generated intermodulation in terms of various parameters of multitransmitter-multireceiver systems. As an example, the level of interference for the configuration to be used in the early Apollo tests has been estimated.

Methods are offered for minimizing or eliminating interference by frequency choice and by filtering. Where doubt exists as to interference level, crucial measurements are suggested.

Introduction

In a multiple transmitter-multiple receiver environment, the principal source of interference is intermodulation in non-linear devices. A non-linear device can be characterized by an equation

$$i = f(e) , \tag{1}$$

where e is the voltage across its terminals, i is the current through its terminals, and f is some non-linear function. If the voltage e consists of the sum of a large voltage and a much smaller voltage, then the function can be expanded in a Taylor series about the large signal operating point. Let

$$e = E + \Delta e \ ; \ \Delta e << E . \tag{2}$$

The Taylor series about the point E is

$$i = i(E) + (\partial i/\partial e)_E \ \Delta e + 1/2 \ (\partial^2 i/\partial e^2)_E \ (\Delta e)^2 + \ldots \tag{3}$$

If E is a sinusoidal voltage and Δe the sum of sinusoids,

$$E = E_a \cos \omega_a t \tag{4}$$

$$\Delta e = \sum_{i=1}^{N} E_i \cos (\omega_i t + \phi_i) \quad . \tag{5}$$

The term $(\partial i/\partial e)_E$ can be expanded in a Fourier series since it is periodic with fundamental angular velocity ω_a hence

$$(\partial i/\partial e)_E = \sum a_n \cos (n\omega_a t + \phi_a) \ . \tag{6}$$

Similarly all the other derivatives $(\partial^n i/\partial e^n)_E$ are sums of the fundamental ω_a and its harmonics.

If one substitutes Eqs. (5) and (6) into Eq. (3), one finds that the term $(\partial i/\partial e)_E \, \Delta e$ yields terms at frequencies $n\omega_a \pm \omega_i$ whose amplitude is proportional to $a_n E_i$. The term $(\partial^2 i/\partial e^2)_E \, (\Delta e)^2$ yields terms at frequencies $n\omega_a \pm 2\omega_i$ and $n\omega_a \pm \omega_i \pm \omega_j$. The terms $(\partial^m i/\partial e^m)_E \, (\Delta e)^m$ yield similar products.

Transmitter Intermodulation

The output of a transmitter has a non-linear current-voltage relationship and can thus be represented by Eq. (1). When frequencies other than that of the transmitter are present, the output current is given by Eq. (3), where E is the voltage generated by the transmitter, and Δe is the voltage of the interfering signals. The power output is proportional to i^2 and hence the powers at various frequencies of interest are given below:

$$P_{3\omega_a \pm \omega_j} = A_{31} P_j P_a \tag{7a}$$

$$P_{2\omega_a \pm \omega_j \pm \omega_k} = A_{22} P_k P_j P_a \tag{7b}$$

$$P_{\omega_a \pm \omega_j \pm \omega_k \pm \omega_\ell} = A_{13} P_j P_k P_\ell P_a \tag{7c}$$

or in general

$$P_{n\omega_a + \sum_{j=1}^{k-n}{}' (\pm \omega_j)} = A_{n(k-n)} \prod_{i=1}^{k-n} P_i P_a \tag{7d}$$

where A_{ij} is a constant of proportionality.

Let us consider a transmitter T_a transmitting at frequency ω_a and n interfering transmitters $T_1, T_2, \ldots, T_n$; the i^{th} transmitter transmitting at ω_i. Let m_{ai} be the fraction of the power from T_i present at T_a and $s_a(i)$ the selectivity of the admitting port of T_a to frequency ω_i.

The power at frequencies $\omega_a \pm \omega_j \pm \omega_k \pm \omega_\ell$ at the terminals of T_a is

$$P_a(\omega_a \omega_j \omega_k \omega_\ell) = a_{13}\,[P_j m_{aj} s_a(j)][P_k m_{ak} s_a(k)][P_\ell m_{a\ell} s_a(\ell)]\, s_a(ajk\ell). \quad (8a)$$

Similarly,

$$P_a(2\omega_a \omega_j \omega_k) = a_{22}\,[P_j m_{aj} s_a(j)][P_k m_{ak} s_a(k)]\, s_a(2ajk) \quad (8b)$$

$$P_a(3\omega_a \omega_j) = a_{31}\,[P_j m_{aj} s_a(j)]\ s_a(3aj) \quad , \quad (8c)$$

where $s_a(ajk\ell)$ is the selectivity of T_a to $\omega_a \pm \omega_j \pm \omega_k \pm \omega_\ell$.

If a receiver (or any of its spurious responses such as image frequencies) is tuned to the intermodulation product and ℓ_a is the fraction of the power at T_a that is present at the receiver terminals, then the receiver power is ℓ_a times the power T_a given by Eq. (8). For computational purposes it is convenient to express Eq. (8) in db. Assuming that all of the transmitters have the same power output P_o, then

$$P_r(\omega_a \omega_j \omega_k \omega_\ell) = A_{13} + M_{aj} + M_{ak} + M_{a\ell} + S_a(j) + S_a(k) + S_a(\ell) + S_a(ajk\ell) + L_a \quad (9a)$$

$$P_r(2\omega_a \omega_j \omega_k) = A_{22} + M_{aj} + M_{ak} + S_a(j) + S_a(k) + S_a(ajk) + L_a \quad (9b)$$

$$P_r(3\omega_a \omega_j) = A_{31} + M_{aj} + S_a(j) + S_a(3aj) + L_a \quad , \quad (9c)$$

where

$$M_{aj} = 10 \log m_{aj} \quad (10a)$$

$$S_a(j) = 10 \log s_a(j) \tag{10b}$$

$$L_a = 10 \log \ell_a \tag{10c}$$

$$A_{rs} = 10 \log a_{rs} P_o^s \tag{10d}$$

With the aid of the above equations, the level of interference can be estimated if the following parameters are known:

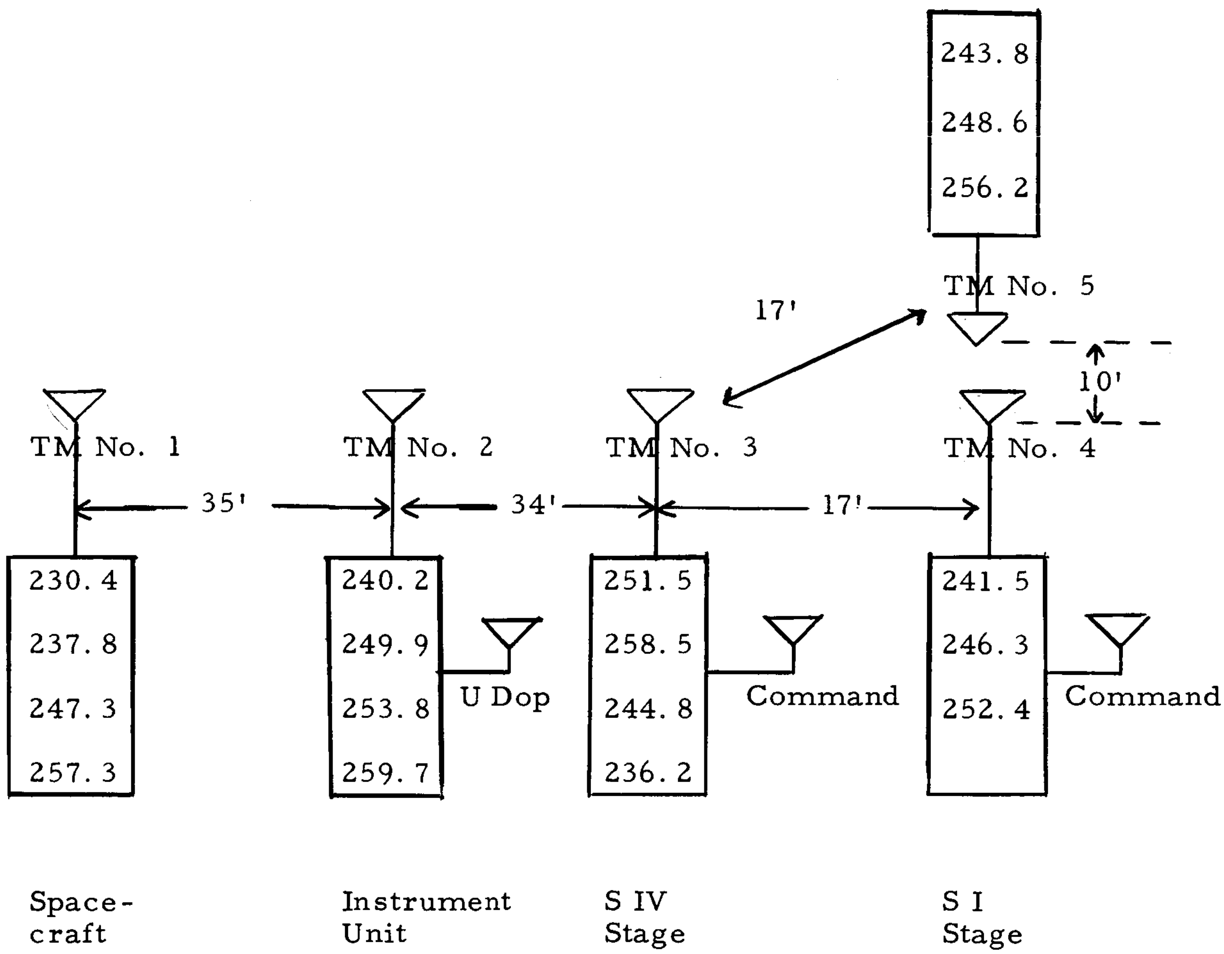
(a) The quantities M_{aj} which are the isolations between the antenna of the transmitter in which the non-linear mixing is occurring and the antennas of the interfering transmitters.

(b) The quantities $S_a(j)$ which are the selectivity of the transmitter, in which mixing is occurring, to signals at the interfering frequencies and the generated frequency. This selectivity includes any filters which are present.

(c) The quantity L_a which is the isolation between the transmitter in which mixing occurs and the receiver. This includes any antenna mismatch due to the generated signal being outside of the band of the transmitting antenna.

(d) The conversion constants A_{rs}.

If these quantities are not known, estimates must be made. Let us consider as an example the system proposed for the early Apollo tests. In this configuration there are eighteen telemetry frequencies being transmitted on five different antennas. The distribution of frequencies recently proposed and physical separation is indicated in Fig. 1.



Apollo Antenna Configuration

Figure 1

In order to evaluate the level of intermodulation using Eq. (9), one must know the electrical isolation between telemetry antennas at the telemetry frequencies as well as the isolation between telemetry and receiving antenna at the receiver frequency L_a. L_a will include the mismatch loss caused by the telemetry antenna designed for the telemetry band transmitting the intermodulation product outside of its bandwidth. In the absence of measurements we shall make pessimistic estimates.

The boundary between the near field and far field of an antenna is approximately* at a distance

$$d = \frac{2L^2}{\lambda} \tag{11}$$

where L is the length of the antenna and λ is the wavelength. The telemetry antennas under consideration are phased pairs of folded monopoles 5.5625 inches long over a ground plane. This is approximately equivalent to a folded dipole of length 11.125 inches. The antenna spacing is in the far field in all cases; therefore, we shall use the far field equation which is

$$\frac{P_r}{P_t} = \frac{G_r G_t \lambda^2}{(4\pi R)^2} \quad , \tag{12}$$

where R is the spacing between antennas, P_r/P_t is the ratio of received to transmitted, and G_r and G_t are the gains of the two antennas in the directions pointing at each other. As mentioned above, each antenna consists of a phased pair which are so phased to produce a minimum along the axis of the vehicle. Choosing G_r and G_t equal to unity will therefore yield less separation than, in

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* Kraus, John D., Antennas, McGraw-Hill Book Co., p. 6 (1950).

fact, exists due to the antenna null. Using this pessimistic assumption yields the values of M_{aj} shown in Table I at 240 Mc.

Antenna Number	2	3	4	5
1	-40	-46	-48.4	-48.4
2	-	-40	-44	-44
3	-	-	-34.4	-34.4
4	-	-	-	-30

Values at M_{aj} isolation between the

Telemetry Antennas at 240 Mc

Table I

The second parameter that must be calculated is L_i, the isolation between the telemetry and receiving antenna. The receiving antenna we shall concern ourselves with is the U Dop antenna since, as we shall see later, there are no intermodulation products formed at the command frequency. As can be seen from Fig. 1, all the telemetry antennas other than No. 2 are in the far field of the U Dop antenna. A second factor which must be taken into account is a mismatch factor. The telemetry antenna radiating an intermodulation product at 450 Mcps is designed for 240-260 Mcps and hence radiates inefficiently at the intermodulation frequency. The efficiency of the antenna at this frequency is difficult to predict since it depends on the impedance characteristics of the antenna. A 10-db loss is probably reasonable. The values of L_a, including this factor, are shown in Table II. The coupling L_2 between the telemetry antenna and the U Dop is estimated at 10 db (plus 10 db for mismatch).

L_1	L_2	L_3	L_4	L_5
-56	-20	-56	-60	-60

Isolation between Telemetry and U Dop Antennas

Table II

Transmitter Selectivity

A third parameter which must be determined before the level of interference can be determined is the selectivity of the telemetry transmitter admitting port to other telemetry frequencies as well as to the intermodulation product. It will be assumed that the four telemetry transmitters in the spacecraft will be multiplexed to their antenna through a resonant cavity device capable of attenuating signals 4 Mcps away by 20 db and signals at 450 ± 5 Mcps by 60 db. These numbers will be used as the total selectivity of the transmitters. It is further assumed that on the output of the other telemetry transmitters there is a filter with 60 db of attenuation above 400 Mcps and that the admitting ports of these telemetry transmitters will provide 5-db selectivity to other telemetry signals 4 Mcps away.

Receiver Sensitivity

To determine whether interference will occur, one must know the threshold of the receiver. A good UHF receiver should have a sensitivity between 0.7 and 2 μ volts. This corresponds to a power of 140 to 150 db down from 100 watts. We will use 150 db as the threshold of the U Dop receiver.

Conversion Factor

The conversion factors A_{rs} for the telemetry transmitters are not known. However, some estimates can be made from past experience and some simple considerations. A_{rs} must be less than 0 db since the non-linearity in the transmitter is a passive device as far as the admitting terminals of the transmitter are concerned. To clarify: the non-linear device may be a vacuum tube with gain fromgrid to plate but the grid viewed as a one terminal pair device, while non-linear, does not deliver additional power to the external circuit, i.e., the antenna, and hence is passive. Values of conversion factors for third order conversion have been measured for various transmitters* and found to be at least 10 db down. Since the fourth order conversion is in most cases smaller, it is reasonable to assume it will be less than -10 db. We are now prepared to calculate the level of interference. It is easily seen that the eighteen telemetry frequencies will not generate any second or third order products at the command or U Dop frequency. The interfering fourth order products are shown in Appendix I where they are grouped into fourteen types. We shall now proceed to discuss each type.

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* "Predicting Interference Levels in Communication Systems," P. Wulfsberg, IRE Convention Record, (1954).

Type I

This is a $3\omega_1-\omega_2$ product where both frequencies are on the spacecraft antenna. Using Eq. (9c) and noting that M_{12} is zero, the condition for no interference is

$$Pr\ (3\omega_1-\omega_2) = A_{31} + S_1(2) + S_1(3\omega_1-\omega_2) + L_1 < -150\text{db}$$

$$= A_{31} - 20 - 60 - 56 < -150\text{db}$$

$$A_{31} < -14\text{db}$$

Type II

This is a $2\omega_1+\omega_2-\omega_3$ product where all three frequencies are on the spacecraft antenna. Using Eq. (9b) with $M_{12} = M_{13} = 0$, the condition for no interference is

$$Pr\ (2\omega_1+\omega_2-\omega_3) = A_{22} + S_1(2) + S_1(3) + S_1(2\omega_1+\omega_2-\omega_3) + L_1 < -150$$

$$A_{22} - 20 - 20 - 60 - 56 < -150$$

$$A_{22} < 6\text{db}$$

Type III

This is a $3\omega_1-\omega_2$ product where ω_1 is on the spacecraft antenna and ω_2 is on a different antenna. The isolation M_{aj} between antennas is at least 40db. Using this value in Eq. (9c) yields

$$Pr\ (3\omega_1-\omega_2) \leq A_{31} - 40 - 20 - 60 - 56 < -150$$

$$A_{31} < 26\text{db}$$

Type IV

This is a $2\omega_1+\omega_2-\omega_3$ product where ω_1 and either ω_2 or ω_3 is on the spacecraft antenna and ω_3 is on a separate antenna. The isolation between the spacecraft antenna, and the other antennas involved is at least 40 db. Using this value in Eq. (9b) yields

$$\Pr(2\omega_1 + \omega_2 - \omega_3) \le A_{22} - 40 - 20 - 20 - 60 - 56 < -150$$

$$A_{22} < 46\text{db}$$

Type V

This is an $\omega_1 \pm \omega_2 \pm \omega_3 \pm \omega_4$ where three of the frequencies are on the spacecraft antenna. Using Eq. (9a) with the same value of M_{aj} as for Types III and IV yields

$$\Pr(\omega_1 + \omega_2 + \omega_3 - \omega_4) \le A_{13} - 40 - 20 - 20 - 20 - 60 - 56 < -150$$

$$A_{13} < 66\text{db}$$

Type VI

This is a $2\omega_1 + \omega_2 - \omega_3$ product where ω_1 is on the spacecraft antenna and ω_2 and ω_3 are on one of the other antennas. M_{aj} and M_{ak} are at least 40 db. Using these values in Eq. (9b) yields

$$\Pr(2\omega_1 + \omega_2 - \omega_3) \le A_{22} - 40 - 40 - 20 - 20 - 60 - 56 < -150$$

$$A_{22} < 86$$

Type VII

This is an $\omega_1 + \omega_2 + \omega_3 - \omega_4$ product where two frequencies are on the spacecraft, and two are on another antenna.

Type VIII

This is a $2\omega_1 + \omega_2 - \omega_3$ product where ω_1 is on the spacecraft antenna, and ω_2 and ω_3 are on different antennas.

Type IX

This is an $\omega_1 + \omega_2 + \omega_3 - \omega_4$ product where two frequencies are on the spacecraft antenna, and the other two are on two different antennas.

Types VII, VIII, and IX clearly produce a smaller interfering signal than Type VI and hence need not be considered.

Type X

This is a $2\omega_2+\omega_1-\omega_3$ product where ω_1 is on the spacecraft antenna, and ω_2 and ω_3 are on antenna No. 2. Equation (9b) yields

$$Pr\ (2\omega_2+\omega_1-\omega_3) = A_{22} + M_{21} + S_2(1) + S_2(3) + S_2\ (2\omega_2+\omega_1-\omega_3) + L_2$$

$$= A_{22} - 40 - 5 - 5 - 60 - 20 < -150$$

$$A_{22} < -20\text{db}$$

Type XI

This is a $2\omega_2+\omega_1-\omega_3$ product where ω_1 is on the spacecraft antenna, ω_2 on antenna No. 2, and ω_3 on a different antenna. M_{aj} is at least 40 db; hence Eq. (9b) yields

$$Pr\ (2\omega_2+\omega_1-\omega_3) = A_{22} + M_{21} + M_{23} + S_2(1) + S_2(3) + S_2(2\omega_2+\omega_1-\omega_3) + L_2$$

$$= A_{22} - 40 - 40 - 5 - 5 - 60 - 20 < -150$$

$$A_{22} < +20\text{db}$$

Type XII

Type XII is an $\omega_1+\omega_2+\omega_3-\omega_4$ product with two frequencies on antenna No. 2, one on No. 1, and one on another. The interference power is less than that of Type XI by 5 db, hence $A_{22} < 25$ db.

Type XIII

The remaining products have only one frequency in the spacecraft and no more than one on antenna No. 2 entering the product.

The largest interfering product in this group is a $3\omega_3-\omega_1$ product where ω_3 is an antenna No. 3, and ω_1 is on the spacecraft. The interference is given by

$$Pr\ (3\omega_3 - \omega_1) = A_{31} + M_{31} + S_3(1) + S_3\ (3\omega_3 - \omega_1) + L_I < -150\text{db}$$

$$= A_{31} - 46 - 5 - 60 - 56 < -150\text{db}$$

$$A_{31} < 17\text{db}$$

Type XIV

These products do not involve spacecraft frequencies.

The only products which might be generated are of Type I and Type IX. An exact measurement would have to be made to determine whether they will in fact occur.

Elimination of Interference by Choice of Frequencies

All fourth order intermodulation products can be eliminated by judicious choice of frequencies. If the frequencies chosen all lie between 238. 3 and 259. 7 Mcps, no interference at 450 ± 5 Mcps will occur.

Proof:

Consider four frequencies: f_1, f_2, f_3, and f_4 lying between 238. 3 and 259. 7 Mcps. The conditions for fourth order intermodulation are

$$445 \leq f_1 + f_2 + f_3 - f_4 \leq 455$$

Let

$$f_1 = 238.3 + X_1$$
$$f_2 = 238.3 + X_2$$
$$f_3 = 238.3 + X_3$$
$$f_4 = 238.3 + X_4$$

where

$$0 \leq X_i \leq 21.4$$

then

$$445 \leq 476.6 + X_1 + X_2 + X_3 - X_4 \leq 455$$

$$-31.6 \leq X_1 + X_2 + X_3 - X_4 \leq -21.6$$

The smallest value $X_1 + X_2 + X_3 - X_4$ can assume is -21.4 which occurs when $X_1 = X_2 = X_3 = 0; X_4 = 21.4$. The above condition therefore cannot be met and hence no fourth order intermodulation is possible.

In the event that changing the frequencies such that all the frequencies lie between 238.3 and 259.7 is not feasible, the problem could greatly be reduced if the frequency at 230.4 is eliminated and one at 255.1 (or any other convenient frequency in the range) be substituted.

If 255.1 is used, only 19 products result (these are shown in Appendix II), none of which are of Types I or X. The largest interference which occurs is Type XIII for which $A_{31} < 17$db. However, since 255.1 lies only 2.2 Mcps from 257.3, the multiplexer requirements in the spacecraft are made somewhat more difficult. It is felt, however, that with this arrangement fourth order intermodulation can be eliminated.

Third Order Intermodulation

If all the frequencies lie between 230.4 and 260 Mcps, the third order products fall between 200.8 and 289.6. The only possible third order interference can occur if the image frequency of one of the equipments lies in this range. It has been proposed that the image frequency of the command transmitter be at 262 Mcps. The number of third order combinations falling in its bandwidth are quite large, and interference may result. It is recommended that either this image frequency be changed or tests be run to determine whether this interference will occur.

Receiver Intermodulation

Receiver intermodulation arises from the mixing of the frequencies in the non-linear receiver front end. Since the interference product is proportional to the products of the power at each frequency, the worst case will be when most of the frequencies are on telemetry antenna No. 2 since L_2 is smallest. The worst case will be Type X which is of the form $2\omega_1 + \omega_2 - \omega_3$ where the ω_1 and ω_3 signals appear across the front end of the receiver at 20 db down from 10 watts and ω_2 at 40 db down. The power across the non-linear element, however, is reduced from this value by the selectivity of the front end. Without actual measurement it is difficult to predict what selectivity is required. However, there is good reason to believe that close to 60 db is required. This would reduce the power of ω_1 and ω_3 to 80 db down from 10 watts and ω_2 to 100 db down. Measurements made on an R278 voice receiver* indicated that third order interference of the type $2\omega_1 - \omega_2$ was generated when ω_1 and ω_2 were each 100 db down from 100 watts. Fourth order products, however, are at a lower level than third order, and 60 db of selectivity will probably suffice. This 60 db can be achieved by a high-pass filter on the input to the receiver which affords 60 db attenuation between 230 and 260 Mcps.

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* "Predicting Interference Levels in Communication Systems," P. Wulfsberg, <u>IRE Convention Record</u> (1954).

Conclusion

Assuming that

(a) the values of antenna separations shown in Tables I and II are valid,

(b) the spacecraft multiplexer gives a 20-db attenuation to the other spacecraft frequencies,

(c) each transmitter has a filter on its output such that a signal above 400 Mcps is attenuated by 60 db,

(d) the Marshall telemetry transmitters have admitting port selectivity of at least 5 db to signals 4 Mcps away,

(e) the receivers have filters on their front ends which attenuate telemetry signals by 60 db,

(f) the receivers do not have image frequencies in the band from 200 to 290 Mcps,

(g) all image frequencies are 60 db down, and

(h) the U Dop receiver is at 450 Mcps and has a bandwidth of ± 5 Mcps,

then

(1) There will be no interference using the set of frequencies shown in Fig. 1 with 230. 4 replaced by 255.1.

(2) If 230. 4 is not replaced, there may be transmitter and/or receiver intermodulation with the following sets:

$$3(230.4) - (237.8) = 453.4$$

$$(230.4) + 2(240.2) - (259.7) = 451.1$$

(3) If assumption h is not valid and the bandwidth is only ±3 Mc, interference may nevertheless occur if,at 453. 4,the rejection is not 10 to 20 db, which is unreasonable to expect.

(4) If assumption (e) is not valid, receiver intermodulation may exist.

(5) If assumption (f) is not valid, third order intermodulation may cause interference.

(6) If the assumptions above are almost met, i. e., a few db, the above conclusion will probably still hold though the new values should be substituted into Eq. (9).

(7) In all cases where interference may be present and changing of conditions to meet assumptions (a) through (h) are not feasible, indicated measurements on individual equipments should be taken to determine whether the interference will occur.

APPENDIX I*

Fourth Order Intermodulation Products Generated by the Frequencies Shown in Fig. 1

Product	Frequencies (÷ 10)			
Type I				
453.4	2304	2304	2304	-2378
Type II				
450.8	2304	2304	2473	-2573
448.7	2304	2378	2378	-2573
451.3	2304	2304	2378	-2473
Type III				
446.4	2304	2304	2304	-2448
455.0	2304	2304	2304	-2362
447.4	2304	2304	2304	-2438
449.7	2304	2304	2304	-2415
451.0	2304	2304	2304	-2402
453.7	2378	2378	2378	-2597
454.9	2378	2378	2378	-2585
Type IV				
454.5	2378	2378	-2573	2362
453.7	2304	2304	-2473	2402
454.3	2304	2304	2473	-2538
448.4	2304	2304	2473	-2597
449.6	2304	2304	2473	-2585
449.7	2304	2304	-2473	2362

*D. Wiggert and E. H. Harvey, Program to Compute Intermodulation Products, AP-20, Lincoln Laboratory, M. I. T. (16 November 1962).

Product	Frequencies (÷ 10)			
451.9	2304	2304	2473	-2562
455.0	2304	2304	-2473	2415
453.4	2304	2304	-2573	2499
455.0	2304	2304	-2573	2515
448.3	2304	2304	-2573	2448
447.3	2304	2304	-2573	2438
452.1	2304	2304	-2573	2486
445.0	2304	2304	-2573	2415
449.8	2304	2304	-2573	2463
452.2	2304	2378	2378	-2538
446.3	2304	2378	2378	-2597
454.5	2304	2378	2378	-2515
447.5	2304	2378	2378	-2585
449.8	2304	2378	2378	-2562
453.6	2304	2378	2378	-2524
448.7	2304	2304	2378	-2499
447.1	2304	2304	2378	-2515
453.8	2304	2304	2378	-2448
454.8	2304	2304	2378	-2438
450.0	2304	2304	2378	-2486
452.3	2304	2304	2378	-2463
446.2	2304	2304	2378	-2524

Type V

Product	Frequencies (÷10)			
451.1	2304	2378	-2573	2402
447.1	2304	2378	-2573	2362
454.7	2304	2378	-2573	2438
452.4	2304	2378	-2573	2415

Type VI

451.1	2304	2304	2402	-2499
447.2	2304	2304	2402	-2538
448.4	2304	2304	2438	-2562
449.9	2304	2304	2415	-2524
454.7	2304	2304	2463	-2524
453.2	2304	2304	2486	-2562
453.3	2378	2378	-2585	2362
451.0	2304	2304	2499	-2597
453.8	2304	2304	2515	-2585
454.1	2304	2304	-2515	2448
445.5	2304	2304	-2515	2362
452.2	2304	2304	-2448	2362

Type VII

452.9	2378	-2573	2362	2362
454.1	2304	-2573	2448	2362
445.5	2304	-2573	2362	2362
452.9	2304	2378	-2515	2362
454.5	2304	2378	-2585	2448
445.9	2304	2378	-2585	2362

Product	Frequencies (÷10)			
453.5	2304	-2573	2402	2402
454.6	2304	2378	2402	-2538
448.7	2304	2378	2402	-2597
	Type VIII			
452.2	2304	2304	2499	-2585
447.1	2304	2304	-2499	2362
454.7	2304	2304	-2499	2438
454.5	2304	2304	2499	-2562
452.4	2304	2304	-2499	2415
454.9	2304	2304	2538	-2597
451.8	2304	2304	-2538	2448
450.8	2304	2304	-2538	2438
448.5	2304	2304	-2538	2415
453.3	2304	2304	-2538	2463
452.6	2304	2304	-2597	2515
445.9	2304	2304	-2597	2448
449.7	2304	2304	-2597	2486
447.4	2304	2304	-2597	2463
453.5	2304	2304	-2597	2524
449.4	2304	2304	2448	-2562
453.2	2304	2304	2448	-2524
453.2	2304	2304	2362	-2438
448.4	2304	2304	2362	-2486
450.7	2304	2304	2362	-2463
453.1	2304	2304	-2515	2438

Product	Frequencies (÷10)			
450.8	2304	2304	-2515	2415
447.1	2304	2304	-2585	2448
446.1	2304	2304	-2585	2438
450.9	2304	2304	-2585	2486
448.6	2304	2304	-2585	2463
454.7	2304	2304	-2585	2524
449.5	2304	2304	2402	-2515
452.4	2304	2304	2402	-2486
454.7	2304	2304	2402	-2463
448.6	2304	2304	2402	-2524
453.7	2304	2304	-2486	2415
446.1	2304	2304	-2562	2415
450.9	2304	2304	-2562	2463
452.2	2304	2304	2438	-2524
452.1	2378	2378	-2597	2362
Type IX				
449.9	2304	2378	2402	-2585
452.2	2304	2378	2402	-2562
454.5	2304	2378	-2499	2362
450.6	2304	2378	-2538	2362
453.3	2304	2378	-2597	2448
452.3	2304	2378	-2597	2438
450.0	2304	2378	-2597	2415
454.8	2304	2378	-2597	2463
451.2	2304	2378	-2585	2415

Product		Frequencies ($\div$10)		
448.2	2304	2378	2362	-2562
452.0	2304	2378	2362	-2524
453.5	2304	2378	-2562	2415
454.2	2304	2473	-2597	2362
449.5	2304	-2573	2402	2362
454.8	2304	-2573	2402	2415
453.5	2304	2378	-2585	2438
453.1	2304	-2573	2362	2438
450.8	2304	-2573	2362	2415
Type X				
451.1	2304	2402	2402	-2597
Type XI				
452.3	2304	2402	2402	-2585
454.6	2304	2402	2402	-2562
Type XII				
453.0	2304	2402	-2538	2362
447.1	2304	2402	-2597	2362
454.7	2304	2402	-2597	2438
452.4	2304	2402	-2597	2415
454.5	2378	2402	-2597	2362

Type XIII

Product	Frequencies (÷10)			
448.3	2304	2402	-2585	2362
453.6	2304	2402	-2585	2415
450.6	2304	2402	2362	-2562
454.4	2304	2402	2362	-2524
452.9	2304	-2499	2362	2362
449.0	2304	-2538	2362	2362
454.3	2304	-2538	2362	2415
451.7	2304	-2597	2448	2362
450.7	2304	-2597	2362	2438
448.4	2304	-2597	2362	2415
453.2	2304	-2597	2362	2463
453.7	2304	-2597	2415	2415
451.3	2304	-2515	2362	2362
452.9	2304	-2585	2448	2362
451.9	2304	-2585	2362	2438
449.6	2304	-2585	2362	2415
454.4	2304	-2585	2362	2463
454.9	2304	-2585	2415	2415
454.2	2304	2362	2362	-2486
446.6	2304	2362	2362	-2562
450.4	2304	2362	2362	-2524
454.2	2304	2362	2483	-2562
451.9	2304	2362	-2562	2415
450.5	2378	-2597	2362	2362

Product	Frequencies (÷10)			
451.7	2378	-2585	2362	2362
454.0	2378	2362	2362	-2562
451.3	2573	-2362	-2362	-2362
	Type XIV			
452.9	2402	-2597	2362	2362
454.1	2402	-2585	2362	2362
454.8	2538	-2362	-2362	-2362
448.9	2597	-2362	-2362	-2362
454.2	2597	-2362	-2362	-2415
450.1	2585	-2362	-2362	-2362
452.4	2362	2362	2362	-2562

APPENDIX II*

Fourth Order Intermodulation Products Generated by Frequencies Shown in Fig. 1 with 230.4 replaced by 255.1

Type	Product	Frequencies (-10)			
III	453.7	2378	2378	2378	-2597
III	454.9	2378	2378	2378	-2585
IV	454.5	2378	2378	-2573	2362
VI	453.3	2378	2378	-2585	2362
VII	452.9	2378	-2573	2362	2362
VIII	452.1	2378	2378	-2597	2362
XII	454.5	2378	2402	-2597	2362
XIII	450.5	2378	-2597	2362	2362
XIII	451.7	2378	-2585	2362	2362
XIII	454.0	2378	2362	2362	-2562
XIII	451.3	2573	-2362	-2362	-2362
XIII	453.5	2551	-2362	-2362	-2362
XIV	452.9	2402	-2597	2362	2362
XIV	454.1	2402	-2585	2362	2362
XIV	454.8	2538	-2362	-2362	-2362
XIV	448.9	2597	-2362	-2362	-2362
XIV	454.2	2597	-2362	-2362	-2415
XIV	450.1	2585	-2362	-2362	-2362
XIV	452.4	2362	2362	2362	-2562

* D. Wiggert and E. H. Harvey, Program to Compute Intermodulation Products, AP-20, Lincoln Laboratory, M. I. T. (16 November 1962).

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